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AN EVALUATION OF THE SLURRY COMPACTION PROCESS FOR THE FABRICATION OF METAL-MATRIX COMPOSITES

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16. Abstract

A fabrication process for producing metal-matrix composites, designated the slurry compaction process, has been developed and evaluated. The process consists of wet-winding filaments through a slurry consisting of a metal powder suspended in a solution of an acrylic resin and organic solvents, drying of the wound composite, and compaction by hot-pressing. Using the slurry compaction process, composites consisting of a pure aluminum matrix reinforced with 26 to 62 percent (by volume) uniaxially alined beryllium filaments of 130-μm (0.005-in.) diameter were fabricated. Reasonable agreement was obtained between the results of tensile and compression tests and rule-of-mixtures predictions. Test results were also compared with those obtained from commercially produced composite specimens fabricated by diffusion bonding. The buckling strength of slurry-compacted composite plates was compared with orthotropic plate theory. Based on the results of this study, the slurry compaction process is considered promising if the problem of filament degradation can be alleviated.

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SUMMARY

A fabrication process for producing metal-matrix composites has been developed and evaluated. The process consists of wet-winding filaments through a slurry consisting of a metal powder suspended in a solution of an acrylic resin and organic solvents, drying of the wound composite, and compaction by hot-pressing. The principal advantage of the slurry compaction process appears to be more uniform packing of the filaments, incorporation of higher filament volume fractions into the fabricated composite, and the potential of blending powders to control filament and matrix interaction. The main disadvantage of the process was the degradation of filament properties which was attributed to uneven flow of the matrix during hot-pressing.

The slurry compaction process was used to fabricate composites consisting of a pure aluminum-matrix reinforced with uniaxially alined beryllium filaments of 130-μm (0.005-in.) diameter which contained filament volume fractions ranging from 0.26 to 0.62. The results obtained from room-temperature tensile and compression tests were compared with rule-of-mixtures predictions and with test results obtained from commercially produced composite specimens having a 2024 aluminum-alloy matrix fabricated by means of diffusion bonding. The tensile and compressive moduli obtained from specimens fabricated by the slurry compaction process agreed well with values predicted by the rule-of-mixtures theory and with values obtained from diffusion bonded specimens. Yield strengths of the slurry compacted specimens were approximately 10 percent below the values predicted by the rule of mixtures whereas the results from the diffusion bonded composites were 30 percent above the predicted values. Ultimate strengths of the slurry compacted and diffusion bonded specimens were found to be below the predicted values by 40 and 20 percent, respectively. The buckling strength of a slurry compacted composite plate having a filament volume fraction of 0.30 was found to agree with orthotropic plate theory, whereas a plate having a filament volume fraction of 0.50 was approximately 30 percent below the value predicted by theory. On the basis of the results of this investigation, the slurry compaction process is considered to have promise as a means of fabricating satisfactory metal-matrix composites if the problem of filament degradation can be alleviated.

INTRODUCTION

The high specific strengths and stiffnesses of filament-reinforced composites make them prime candidate materials for use in the fabrication of lightweight aerospace and aeronautical structures. Present-day composites are normally classified by the nature of their matrices into either resin- or metal-matrix systems. Although considerably behind resin-matrix systems in their development, metal-matrix composites offer potential as structural materials because their higher strengths and elastic moduli of the matrices provide for better transverse properties and greater resistance to failure by compressive buckling. Metal-matrix systems can also be utilized in environments where resin-matrix composites are not suitable. However, metal-matrix systems have been slow to develop, relative to resin-matrix composite materials, as a consequence of the economic and technical problems associated with their fabrication.

This investigation was undertaken to determine the feasibility of developing a fabrication technique for producing metal-matrix composites which would overcome some of the difficulties associated with their fabrication, such as filament misalinement, difficulty in attaining high filament volume fractions, undesirable filament and matrix reactions, and incomplete infiltration of the matrix around the filaments. The technique developed in this study is designated as the slurry compaction process and was used to fabricate pure aluminum matrices reinforced with uniaxially alined beryllium filaments having filament volume fractions ranging from 0.26 to 0.62. Evaluation of the fabrication process included the determination of the tensile properties of the filament, the tensile and compressive properties of the matrix, and an investigation of the tensile, compressive, and plate buckling behavior of composites containing various filament volume fractions.

As a means of evaluating the slurry compaction process as compared with an alternate fabrication method, a limited number of commercially fabricated composite specimens were procured and tested. These composites were fabricated by diffusion bonding stacked alternate monolayers of 2024 aluminum-alloy foil and uniaxially alined beryllium filaments. The tensile and compressive properties of the procured specimens were compared with the results obtained from the composite fabricated by the slurry compaction technique. A metallurgical investigation was also conducted to aid in determining the effect of various fabrication parameters and to attempt to define the nature of the bond existing between the matrix and filaments of composites fabricated by both processes.

SYMBOLS

The units used for physical quantities defined in this paper are given both in the miscellaneous units used herein and in the International System of Units (SI). Conversion factors pertinent to the present investigation are presented in appendix A and reference 1. Symbols used to represent physical and mechanical properties throughout this paper are listed below.

b	width of plate between knife edge side supports, meter (inch)
E	modulus of elasticity, newtons/meter^2 (pounds force/inch^2)
G_{LT}	shear modulus associated with shearing stresses applied parallel and perpendicular (in the plane of the sheet) to the beryllium filaments in a unidirectional beryllium-aluminum composite, newtons/meter^2 (pounds force/inch^2)
R	radius of curvature, meter (inch)
t	sheet thickness, meter (inch)
V	volume fraction, ratio of constituent volume to total volume
ϵ	strain
ζ	reinforcement correlation factor (see eq. (2))
η	intermediate factor (see eq. (2))
μ	Poisson's ratio
ξ	empirical factor (see eq. (5))
σ	stress, newtons/meter^2 (pounds force/inch^2)

Subscripts:

c	composite
cr	buckling
e	effective

E	pertaining to elastic modulus
f	filament
G	pertaining to shear modulus
L	longitudinal (parallel to filaments and sheet length)
m	matrix
max	maximum
T	transverse (perpendicular to filaments – parallel to sheet width)
ult	ultimate
y	yield

FABRICATION PROCEDURES

Slurry Development

The powder selected for inclusion in the slurry was 99.0 percent pure aluminum and was 95 percent -325 mesh, having an average particle size of 25 micrometers. The use of several aluminum powders having larger and smaller average particle sizes was investigated but was found to be unsatisfactory as a result of inadequate sintering or drying characteristics. The acrylic resin selected for use in preparing the slurry was one which vaporized at 700 K (800° F) leaving no detectable residue. Various combinations of aluminum powder, binder, and solvents were studied to obtain a slurry that would possess sufficient strength after drying to facilitate handling and to maintain filament alinement prior to hot-pressing. The nominal composition of the slurry used in this study is indicated in table I.

Composite Fabrication by Slurry Compaction

The composite system utilized in this study consisted of a pure aluminum matrix reinforced with beryllium filaments of 130-μm (0.005-in.) diameter. These filaments were drawn from a cast ingot and subsequently annealed.

The four-step slurry compaction process developed is illustrated in figure 1. The first step consisted of wet winding the beryllium filaments onto a suitable mandrel by using the apparatus shown in figure 2. The beryllium filaments were passed through the slurry bath and were uniformly coated as they were wound onto the mandrel. The volume of filaments incorporated into the composite was dependent primarily on the rate of rotation of the mandrel since this movement controlled the packing arrangement of the filaments. After winding the required number of layers, a cover sheet of aluminum foil was added to prevent damage from handling. The wound composite was then oven dried at 366 K (200° F) for 16 to 20 hours to remove the volatile organic solvents and to harden the composite by the thermo-setting nature of the acrylic resin. Hardening of the matrix maintained alinement of the beryllium filaments and facilitated removal of the composite from the mandrel. Each dried composite plate produced in this manner was positioned in dies and enclosed in an aluminum foil envelope which was purged for approximately 10 minutes with argon. While under a preload corresponding to approximately 70 kN/m^2 (10 psi), the composite was heated to 700 K (800° F) and held for 15 minutes to allow the acrylic resin to vaporize. The temperature was then increased to 866 K (1100° F) and the desired pressure of 55 MN/m^2 (8000 psi) was applied and maintained for 30 minutes. The parameters used to hot-press the composites were based on the results of an optimization study on the mechanical properties of the hot-pressed slurry matrix. Several unreinforced pure aluminum-matrix plates were produced by use of these parameters and were tested to provide baseline data on the matrix.

Composite Fabrication by Diffusion Bonding

One 2024 aluminum-alloy matrix material plate and one 41 volume percent beryllium-2024 aluminum-alloy composite plate were procured from General Technologies Corporation, Reston, Virginia. Each plate measured 5.1 by 10.2 by 0.64 cm (2 by 4 by 1/4 in.) and was fabricated by the diffusion bonding process. The matrix material plate was hot-pressed by use of the same parameters utilized for the filament reinforced plate. The composite plate was prepared by winding beryllium wire, supplied by NASA Langley, onto a circular mandrel 0.3 m (1 ft) in diameter over a single ply of 2024 aluminum-alloy foil 130 μm (0.005 in.) thick. A polystyrene coating was sprayed on the winding to hold the beryllium filament in place. Monolayer preforms were then cut to size and stacked to form the pressing blank. The pressing blank was then placed in a die and diffusion bonded at a temperature of 755 K (900° F) and a pressure of 55 MN/m^2 (8000 psi) for a period of 1 hour.

SPECIMENS AND TEST PROCEDURES

Specimens

Configurations of composite tensile specimens fabricated by the slurry process and by the diffusion bonding process are shown in figure 3. Compression specimen configurations are shown in figure 4. All specimens were machined from plate material. Size limitations of the procured diffusion bonded material resulted in modification of specimen configuration. Similar tensile and compression specimens were machined from unreinforced matrix material. The plate-buckling-specimen configuration for plates fabricated by the slurry process is shown in figure 5.

Test Procedures

Tensile tests.- Composite material tensile tests were conducted at room temperature at a strain rate of 0.005 per minute to the yield stress and at an increased head speed corresponding to a strain rate of 0.05 per minute from yield to failure. Strain was determined from foil-type strain gages placed on opposite faces of the specimen.

Compression tests.- Compression tests of the fabricated composites were made by utilizing the fixture shown in figure 6. The ends of the specimen were clamped using the T-shaped arrangements to prevent local crippling of the ends while the face supports were used to prevent column buckling. A biaxial foil type strain gage, attached to each face of the specimen through the opening in the face supports, measured longitudinal and transverse strains. Tests were made at room temperature at a strain rate of 0.0025 per minute.

Plate-buckling tests.- Plate-buckling tests of slurry compacted composites were performed with the test apparatus shown in figure 7. The plate edges were supported by knife-edge fixtures having a 0.04-cm $\left(\frac{1}{64}\text{-in.}\right)$ radius. The overall length of the fixture was 0.64 cm (0.25 in.) shorter than the specimen to insure proper loading of the plate. Tests were conducted at room temperature at a strain rate of 0.0025 per minute. Head deflection and buckle amplitude were measured by linear differential transformers, while longitudinal and transverse strains were measured by a biaxial strain gage mounted in the center of each face.

RESULTS AND DISCUSSION

Mechanical Properties

Evaluation of a fabrication process for producing metal-matrix composites necessitates an investigation of the mechanical and metallurgical nature of the composites to determine whether an effect is attributable to the composite system being studied or to the fabrication process. This section presents the mechanical properties and results of a mechanical and metallurgical investigation of beryllium-aluminum composite specimens produced by the slurry compaction process as well as the results obtained from a limited number of specimens produced by the diffusion bonding process.

Tensile properties.- The tensile properties of aluminum reinforced with uniaxially alined beryllium filaments were obtained from specimens having filament volume fractions ranging from 0.26 to 0.55. These data are presented in table II. It has been shown that the mechanical properties of a metal-matrix composite often obey the rule of mixtures (ref. 2). This rule simply states that a linear relationship exists between the properties of a composite and the sum of the products of the volume fractions and properties of each of the components as shown for the modulus of a composite by the following equation:

$$E_c = E_f V_f + E_m \left(1 - V_f\right) \tag{1}$$

A similar relationship is also used for predicting the yield strength, ultimate strength, and Poisson's ratio. The experimentally determined constituent properties used for rule-of-mixtures calculations are presented in table III.

The elastic modulus values obtained from tension tests conducted on composites fabricated by the slurry compaction process are presented in figure 8 along with two data points obtained from tensile tests on the diffusion bonded composites. The data shown for the composites fabricated by the slurry compaction process possessed beryllium filament volume fractions ranging from 0.26 to 0.55 while the diffusion bonded composites contained filament volume fractions of 0.41. The tensile elastic moduli of both the slurry compacted and diffusion bonded composites show good agreement with rule-of-mixtures calculations.

The tensile 0.2-percent offset yield strength of the beryllium-aluminum composite is plotted in figure 9 and compared with the rule-of-mixtures theory. Two lines are shown for the rule-of-mixtures values because the matrix material for composites fabricated by each process differed. The experimental yield strength values obtained for the composite specimens fabricated by means of the slurry technique were generally below the values predicted by the rule of mixtures, whereas experimental values for the specimens fabricated by the diffusion bonding process, having a 2024 aluminum matrix, were approximately 25 percent above the rule-of-mixtures values.

A similar plot of the ultimate strength of the composite as a function of filament volume fraction is shown in figure 10. The ultimate strength of the specimens fabricated using the slurry technique was approximately 40 percent below the values predicted by the rule of mixtures while the diffusion bonded specimen data are approximately 20 percent below the rule of mixtures.

Discrepancies between the experimental and predicted values of the magnitude noted in figures 9 and 10 suggest the possibility of filament degradation since the strength of the filament is the controlling factor in the strength of the composite. The strength of the filaments realized in the slurry compacted composites was estimated using a modified rule of mixtures as shown in figure 10. A line was drawn through the ultimate-strength data for the slurry compacted composites, on the assumption that no degradation occurred in matrix properties, which indicated that the strength of the filaments within the fabricated composites was approximately 655 MN/m^2 (95 ksi).

In an attempt to determine the cause of filament degradation, filaments were extracted from fabricated composites for examination and testing by leaching away the matrix by use of a warm sodium-hydroxide solution. Examination of filaments extracted from composites fabricated by the slurry compaction process under a light microscope indicated that the filaments possessed a series of local deformation of kinks as shown in figure 11. Distortions of the nature observed could result in points of stress concentrations and misalinement of the bent portion of the filament in the composite which would reduce the load-carrying ability of the material. Tensile tests conducted on filaments extracted from the slurry compacted composites showed that the ultimate strength of the filaments decreased from 1104 to 690 MN/m^2 (160 to 100 ksi), which is within 5 percent of the value indicated by the modified rule of mixtures in figure 10. Therefore, distortions of the filaments during fabrication appear to account for the low values of ultimate strength obtained for the slurry compacted composites. Such distortions could result from agglomeration of powder particles in the slurry resulting in uneven plastic flow of the matrix during hot-pressing or consolidation of the composite. Consequently, it may be possible to alleviate the problem by better dispersion of the metal powder in the slurry.

Filaments were also extracted from the diffusion bonded composites and examined by light microscopy as shown in figure 12. There was no observable distortion of the filaments. However, it was apparent that the filaments had been etched by the leaching solution. Test results obtained on these filaments showed that the ultimate strength had decreased by approximately 30 percent as compared with the strength of the as-received filaments. The reduction in strength of the filaments was attributed to reaction of the leaching solution with the outer periphery of the filament. The lack of a similar reaction between the leaching solution and the filaments extracted from the slurry compacted composites would indicate the possibility of diffusion between the 2024 aluminum-alloy matrix and the beryllium filaments which could result in a region more susceptible to attack by the leaching solution. Diffusion of copper from the matrix into the beryllium filament could also explain the apparent synergistic effects noted for the yield strength of the diffusion bonded composites, as discussed further in the section on metallurgical investigation.

Compression properties.- The compressive properties of the fabricated composites containing filament volume fractions from 0.26 to 0.62 are recorded in table IV. A comparison of the compressive elastic modulus data with the rule-of-mixtures prediction for specimens fabricated by both techniques is shown in figure 13. The compressive modulus of both the slurry compacted and diffusion bonded composites was in good agreement with the values predicted by the rule of mixtures.

The compressive yield strength data are plotted in figure 14 where the experimental values for the slurry compacted composites are shown to be approximately 15 percent below the predicted values. The reason for this discrepancy is again attributed to filament degradation during hot-pressing. The yield strength values for the diffusion bonded composites are shown to exceed the predicted values by approximately 30 percent. This result is discussed subsequently, along with the tensile yield values, in the section "Metallurgical Investigation."

Plate buckling characteristics.- The buckling strengths of four beryllium-aluminum composite plate buckling specimens, fabricated by the slurry compaction process and having filament volume fractions which varied from 0.29 to 0.51, were determined by the top-of-the-knee method applied to buckle amplitude (ref. 3). The maximum postbuckling strengths of the plates were also determined. The beryllium filaments in the plates were oriented parallel to the plate lengths, and the plates were tested with loaded ends clamped and unloaded edges simply supported. Constituent properties applicable to the plates and based on reference 4 and handbook values are given in table V. A discussion of the theoretical behavior of the plates, based on orthotropic plate theory, is presented in appendix B along with the equations used to calculate the results of table VI(a).

The experimental results of the four plate-buckling tests are presented in table VI(b). Plates 2 and 3 each developed a small longitudinal crack during testing and as a consequence the data obtained from them is questionable. A comparison of the compressive stress-strain curve of the material with experimental and theoretical stress—unit-shortening curves for plates 1 and 4 is shown in figure 15. The unit shortening was determined by dividing the total shortening (machine head deflection) of the plate by 19.0 cm (7.5 in.). (See fig. 5.) Values of unit shortening computed in this manner were in agreement with strains measured with the biaxial foil-type strain gages. Strain reversal was also noted to occur at the stress at the top-of-the-knee of stress-buckle amplitude curves. A significant increase in buckling stress and maximum stress with increased filament fraction is indicated in figure 15. However, plate 1 exceeded its theoretical buckling stress by approximately 10 percent, whereas the buckling stress for plate 4 was almost 28 percent below the theoretical value. The values of buckling strain for the plates are well within the elastic range of the beryllium filaments and at slightly less than the proportional limit strain of the aluminum matrix for plate 1 and somewhat beyond the proportional limit strain for plate 4. Thus, the onset of plasticity in the matrix could have had a marked effect on the buckling stress. It appears that alloying of the matrix to increase the range of elasticity may prove to be as important as the filament volume fraction in determining the buckling stress. The comparison between theoretical and experimental maximum postbuckling strengths is probably also affected by plasticity in the matrix. The results also suggest that a 0.1-percent offset yield stress and associated strain (appendix B) would provide closer agreement between theory and experiment.

Metallurgical Investigation

A metallurgical investigation of the fabricated composites was conducted in an attempt to better define the nature of the interface of the filaments and matrix and to aid in explaining the deviation of experimental data from the rule-of-mixtures predictions. A typical light photomicrograph of an etched and unetched section of a beryllium-aluminum composite fabricated by the slurry compaction process is shown in figure 16. Spacing of the filament is shown to be fairly uniform with no filament-to-filament contact. The interface between the filament and the matrix is somewhat rough and irregular. However, the irregularity of the surface of the filament is characteristic of filaments drawn from a cast ingot (ref. 4) and is not a result of interaction of the filament and matrix (ref. 5).

Light photomicrographs of an etched and unetched diffusion bonded composite specimen are shown in figure 17. Spacing of the filaments in the diffusion bonded composite is not as uniform as it is in the slurry compacted composites. The third phase shown, which is visible in the matrix of both photomicrographs, is the copper-magnesium-aluminum precipitate ($CuMgAl_2$) which is common to 2024 aluminum alloy. The etched photomicrograph shows that the precipitate has been selectively attacked by the etching agent and, unlike the etched photomicrograph of the slurry composite, the outer periphery of the filament also appears to have been attacked. If the etched and unetched photomicrographs are compared, it is apparent that the dark region surrounding the filament in the etched photomicrograph results from etching of the filament and not the matrix. This effect would indicate the possibility of a varying composition of the filament resulting from interaction with the matrix.

As a result of the indications of a possible reaction noted on the photomicrographs, an electron microprobe analysis of the interface was made. A trace for copper was made across the filament since the copper contained in the 2024 aluminum is soluble in beryllium at the temperature of composite fabrication. The results obtained indicated that the concentration of copper in the vicinity of the outer periphery of the filament was approximately $2\frac{1}{2}$ times as great as in the matrix near the interface. This result indicates that diffusion of copper into the filament occurred during fabrication. Diffusion of copper into the beryllium would establish a metallurgical bond between the filament and the matrix which could possibly prevent or retard lateral contraction of the filaments during testing. Restraint of this nature could possibly increase the effective yield strength and at least partially account for the apparent synergism noted previously for the yield of the diffusion bonded composite.

CONCLUDING REMARKS

The fabrication of a uniaxially reinforced beryllium-aluminum composite employing the slurry compaction technique has been investigated, and the test results obtained from fabricated specimens have been compared with values predicted by the rule of mixtures and with results obtained from beryllium-aluminum composites fabricated by diffusion bonding.

The modulus and yield strength values obtained from tension and compression specimens fabricated by the slurry process agree well with the values predicted by the rule of mixtures whereas the ultimate-strength values of the slurry specimens were lower than the predicted values by 40 percent, probably because of filament distortions. The buckling behavior of a uniaxially reinforced plate having a filament volume fraction of 0.30 conformed to orthotropic plate theory; however, the plate having a volume fraction of 0.50 deviated from this theory by approximately 30 percent, apparently because of plasticity effects.

The results obtained from beryllium-aluminum composites having a 2024 aluminum-alloy matrix and fabricated by means of diffusion bonding agreed well with the rule-of-mixtures predictions. Better agreement between predicted and experimental values of yield and ultimate strength for the diffusion bonded composite was attributed to better filament-to-matrix bonding.

The slurry compaction process is considered to have promise as a means of fabricating metal-matrix composites if the problem of filament distortion can be alleviated. The potential of incorporating higher filament volume fractions into the composite, and the possibility of blending powders to control filament and matrix interactions as well as the capability of more uniform filament spacing would seem to warrant further investigation of the process.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., December 8, 1970.

APPENDIX A

CONVERSION OF MISCELLANEOUS UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures in Paris, October 1960. Factors required for converting the miscellaneous units used herein to the International System of Units (SI) (ref. 1) are given in the following table:

Physical quantity	Miscellaneous unit	Conversion factor (*)	SI unit (**)
Force	lbf	4.44822	newtons (N)
Length	in.	0.0254	meters (m)
Temperature	$^{\circ}F$	(5/9)(F + 460)	kelvins (K)
Stress, pressure . .	ksi = kips/in^2	6.895×10^6	newtons/meter^2 (N/m^2)
Modulus	psi = lbf/in^2	6895	newtons/meter^2 (N/m^2)
Volume	liter	10^{-3}	meters^3 (m^3)
Viscosity	centipoises	10^{-3}	newton-seconds/meter^2 (N-s/m^2)

*Multiply value given in miscellaneous unit by conversion factor to obtain equivalent value in SI unit.

**Prefixes to indicate multiple of units are as follows:

Prefix	Multiple
giga (G)	10^9
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}

APPENDIX B

THEORETICAL BUCKLING BEHAVIOR

Presented herein are the considerations and assumptions used to develop the theoretical stress—unit-shortening curves of figure 15 and the calculated values of table VI(a).

Constituent properties applicable to the plates are given in table V. The longitudinal elastic constants (table VI(a)) are based on the rule of mixtures while the Halpin-Tsai equation (ref. 6) was used to predict the transverse elastic constants and is presented here in the present notation:

$$\frac{E_T}{E_m} = \frac{1 + \zeta_E \eta V_f}{1 - \eta V_f} \tag{2}$$

where

$$\eta = \frac{\dfrac{E_f}{E_m} - 1}{\dfrac{E_f}{E_m} + \zeta_E}$$

A corresponding equation exists for G_{LT}. The theoretical values of ζ_E and ζ_G of 2 and 1, respectively, were used in the calculations. Transverse Poisson's ratios were calculated by

$$\mu_T = \mu_L \frac{E_T}{E_L} \tag{3}$$

The elastic constants evaluated in this manner were then used to determine the theoretical critical buckling stress. Buckling calculations were based on the orthotropic plate buckling formula for a long plate with all sides simply supported (for example, ref. 7):

$$\sigma_{cr} = \frac{\pi^2}{6\left(1 - \mu_L \mu_T\right)(b/t)^2}\left[\sqrt{E_L E_T} + E_L \mu_L + 2G_{LT}\left(1 - \mu_L \mu_T\right)\right] \tag{4}$$

Additional calculations were made for plates of finite length with clamped loaded edges, but these effects were found to be negligible.

Inspection of the calculated elastic constants reveals that the composite plates were only mildly orthotropic; thus, the theoretical stress-unit-shortening curves of figure 15 were computed with the aid of the following isotropic, effective width formula:

$$\frac{b_e}{b} = \xi \sqrt{\frac{\epsilon_{cr}}{\epsilon}} \tag{5}$$

which is presented in reference 8. The empirical factor ξ was evaluated as

$$\xi = 1 + 0.28\left(1 - \sqrt{\frac{\epsilon_{cr}}{\epsilon}}\right)^3 \tag{6}$$

To estimate the maximum postbuckling strength of the plates, the following crippling formula (ref. 9) was used:

$$\sigma_{max} = \sqrt{\epsilon_{cr}}\left(\frac{\xi \sigma_y}{\sqrt{\epsilon}}\right)_{max} \tag{7}$$

The assumption was made that the quantity $\left(\xi \sigma_y / \sqrt{\epsilon}\right)$ is a maximum at the 0.2-percent offset yield strength of the material.

REFERENCES

1. Comm. on Metric Pract.: ASTM Metric Practice Guide. NBS Handbook 102, U.S. Dep. Com., Mar. 10, 1967.

2. McDanels, David L.; Jech, Robert W.; and Weeton, John W.: Stress-Strain Behavior of Tungsten-Fiber-Reinforced Copper Composites. NASA TN D-1881, 1963.

3. Hu, Pai C.; Lundquist, Eugene E.; and Batdorf, S. B.: Effect of Small Deviations From Flatness on Effective Width and Buckling of Plates in Compression. NACA TN 1124, 1946.

4. Schwartz, H. S.: Mechanical Behavior of Beryllium Wire Reinforced Plastic Composites. Pt. I. Static Mechanical Properties. AFML-TR-66-404, Pt. I, U.S. Air Force, Jan. 1967. (Available from DDC as AD 657 309.)

5. Hansen, Max; and Anderko, Kurt: Constitution of Binary Alloys. Second ed., McGraw-Hill Book Co., Inc., 1958, pp. 73-74.

6. Ashton, J. E.; Halpin, J. C.; and Petit, P. H.: Primer on Composite Materials: Analysis. Technomic Pub. Co., Inc., c.1969, pp. 77-84.

7. Lekhnitskii, S. G. (S. W. Tsai and T. Cheron, transl.): Anisotropic Plates. Gordon and Breach Sci. Publ., c.1968, pp. 278-279 and 447.

8. Peterson, James P.; Whitley, Ralph O.; and Deaton, Jerry W.: Structural Behavior and Compressive Strength of Circular Cylinders With Longitudinal Stiffening. NASA TN D-1251, 1962.

9. Davis, John G., Jr.; and Zender, George W.: Compressive Behavior of Plates Fabricated From Glass Filaments and Epoxy Resin. NASA TN D-3918, 1967.

TABLE I. - SLURRY COMPOSITION

Material	Weight, percent
Aluminum powder (-325 mesh, 99% pure)	71.6
Rohm-Haas, B-66 acrylic resin	5.1
Monoethyl ether	20.1
Monobutyl ether	3.2

TABLE II. - TENSILE PROPERTIES OF BERYLLIUM-ALUMINUM COMPOSITES

V_f	t		E		σ_y		σ_{ult}		Elongation, percent
	cm	in.	GN/m^2	psi	MN/m^2	ksi	MN/m^2	ksi	
Slurry compacted									
0.26	0.069	0.027	129	18.7×10^6	200	29.0	213	30.9	1.0
.28	.071	.028	108	15.7	194	28.2	250	36.3	7.0
.29	.071	.028	95	13.8	190	27.6	226	32.8	5.0
.42	.086	.034	153	22.2	332	48.1	340	49.4	2.7
.43	.086	.034	146	21.2	320	44.1	336	48.7	6.0
.44	.137	.054	145	21.0	290	40.5	364	52.7	6.5
.44	.086	.034	159	23.0	342	44.6	360	52.1	4.7
.47	.133	.052	162	23.5	319	46.2	364	52.7	3.0
.50	.137	.054	175	25.4	326	47.3	401	58.3	6.0
.51	.137	.054	175	25.4	336	48.8	423	61.4	7.0
.55	.137	.054	190	27.5	365	52.4	430	62.4	5.0
Diffusion bonded									
0.41	0.210	0.082	149	21.6×10^6	458	66.5	514	74.5	5.5
.41	.198	.078	135	19.6	454	65.8	516	74.8	6.0

TABLE III.- CONSTITUENT PROPERTIES

Constituent	Material	Test mode	E		σ_y		σ_{ult}		Elongation, percent
			GN/m^2	psi	MN/m^2	ksi	MN/m^2	ksi	
Matrix	Slurry compacted pure aluminum	Tension	62	9.0×10^6	50	7.3	109	15.7	26
		Compression	69	10.0×10^6	59	8.6	----	----	---
	Diffusion-bonded 2024 aluminum	Tension	77	11.2×10^6	150	21.8	304	44.0	13
		Compression	77	11.1×10^6	158	22.9	----	----	---
Filament	Beryllium	Tension	240	34.8×10^6	717	104	1110	161	2

TABLE IV.- COMPRESSIVE PROPERTIES OF BERYLLIUM-ALUMINUM COMPOSITES

V_f	t		E		σ_y	
	cm	in.	GN/m^2	psi	MN/m^2	ksi
Slurry compacted						
0.26	0.081	0.032	118	17.1×10^6	176	25.4
.27	.081	.032	125	18.1	196	28.4
.28	.081	.032	119	17.3	194	28.2
.47	.137	.054	168	24.4	338	49.0
.47	.096	.038	163	23.7	326	47.3
.48	.096	.038	141	20.5	---	---
.51	.140	.055	161	23.4	312	45.3
.51	.096	.038	143	20.8	311	45.1
.52	.137	.054	163	23.6	344	50.0
.52	.137	.054	150	21.8	396	43.0
.56	.137	.054	174	25.2	349	50.6
.62	.137	.054	155	22.5	354	51.9
Diffusion bonded						
0.40	0.198	0.078	157	22.8×10^6	488	70.8
.40	.198	.078	156	22.6	474	68.6

TABLE V.- CONSTITUENT PROPERTIES FOR PLATE BUCKLING SPECIMENS

Material	E		μ	G_{LT}		σ_y		ϵ_y
	GN/m^2	psi		GN/m^2	psi	MN/m^2	ksi	
Beryllium	240	$^*35 \times 10^6$	0.03	117	17×10^6	717	104	0.003
Aluminum (pure)	69	10×10^6	0.33	28	4×10^6	62	9	0.005

* From reference 4.

TABLE VI. - PLATE BUCKLING RESULTS

(a) Calculated

Plate	E_L		E_T		μ_L	μ_T	G_{LT}		σ_{cr}		σ_{max}	
	GN/m^2	psi	GN/m^2	psi			GN/m^2	psi	MN/m^2	ksi	MN/m^2	ksi
1	119	17.3×10^6	101	14.6×10^6	0.242	0.205	37.8	5.48×10^6	67.6	9.8	106.2	15.4
2	128	18.6	108	15.6	.226	.190	40.5	5.87	64.8	9.4	113.1	16.4
3	156	22.6	130	18.9	.178	.149	50.6	7.34	174.5	25.3	213.0	30.9
4	157	22.7	132	19.1	.176	.148	51.0	7.40	189.7	27.5	224.8	32.6

(b) Experimental

Plate	V_f	$(b/t)^2$	E_L		σ_{cr}		σ_{max}	
			GN/m^2	psi	MN/m^2	ksi	MN/m^2	ksi
1	0.29	5280	121	17.6×10^6	74	10.8	99	14.3
[a]2	.34	5670	110	15.9	62	9.0	94	13.6
[a]3	.51	2570	170	24.7	107	15.6	132	19.1
4	.51	2375	167	24.2	137	19.9	165	24.0

[a] Longitudinal crack developed during test.

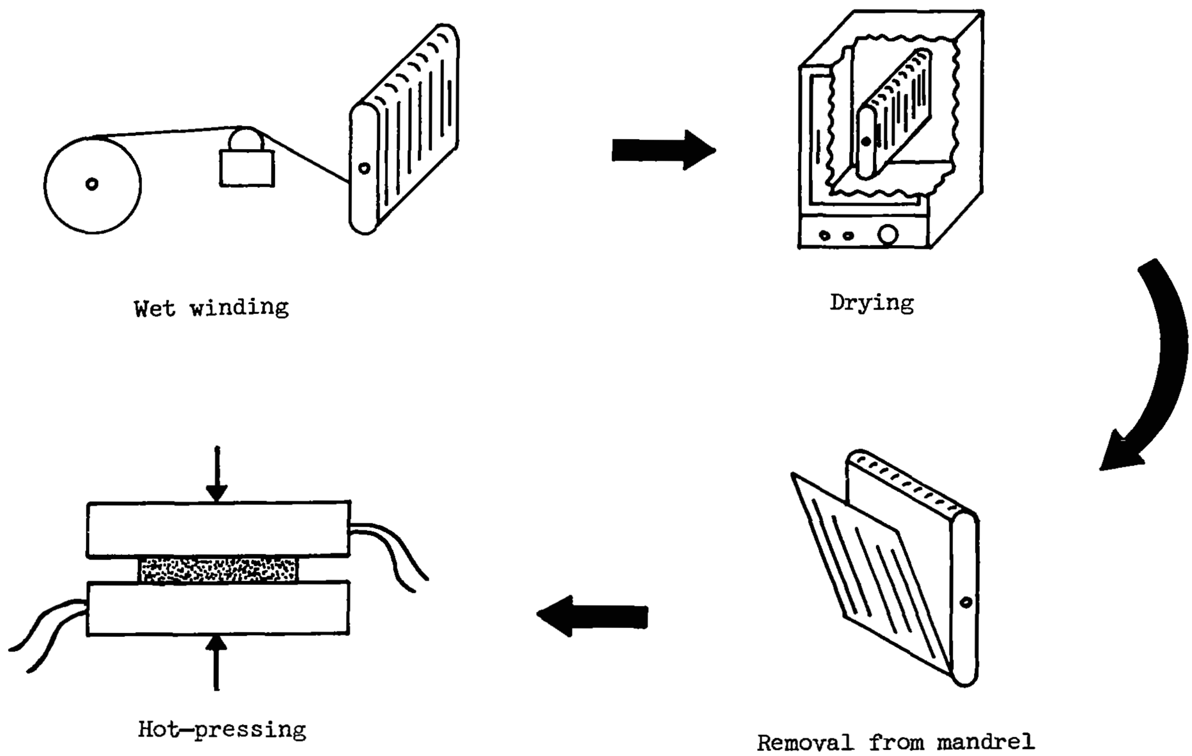

Figure 1.- Flow sheet of slurry compaction process.

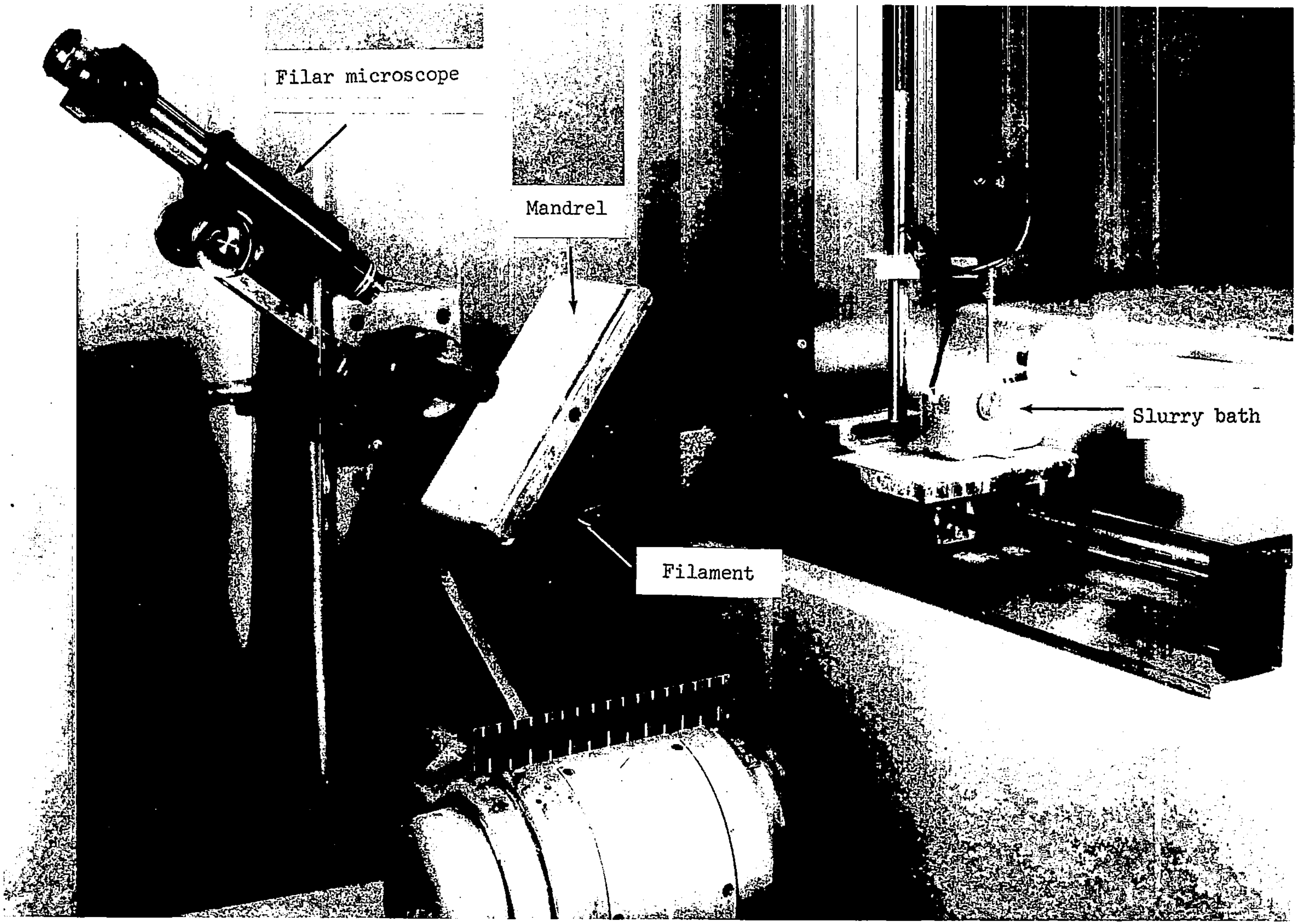

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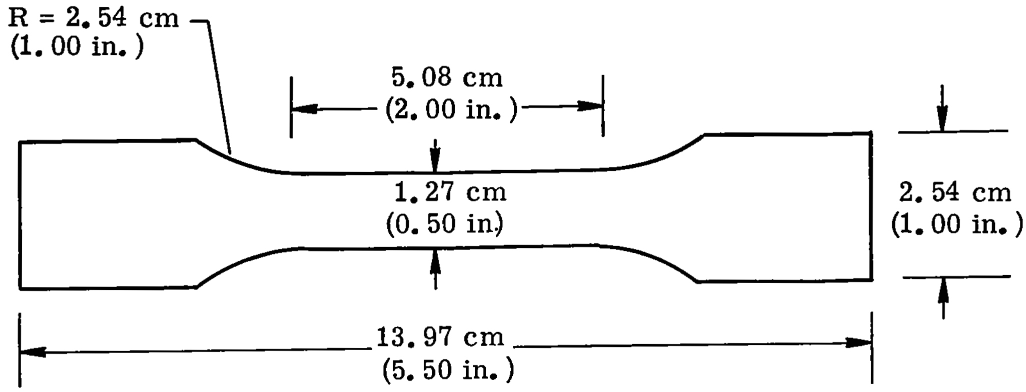
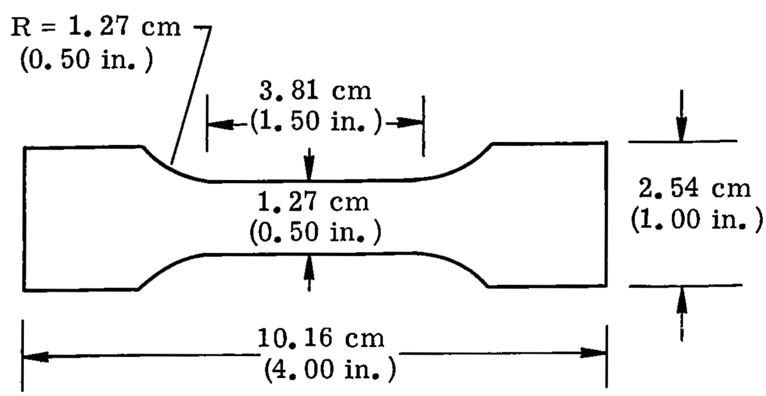
Figure 2.- Filament winding apparatus.

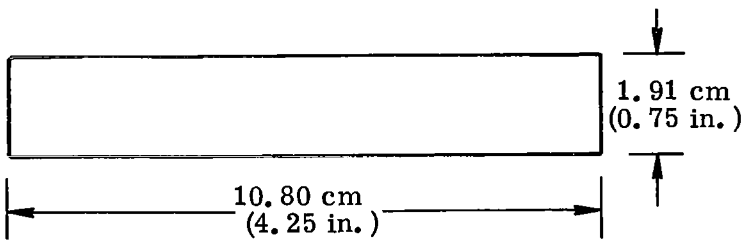


(a) Slurry compacted.

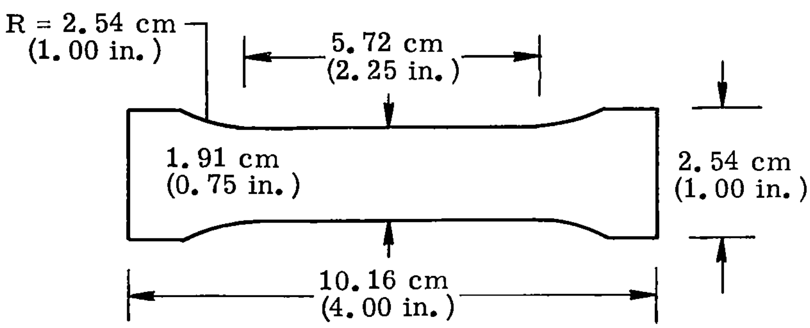


(b) Diffusion bonded.

Figure 3.- Tensile specimen configurations.



(a) Slurry compacted.



(b) Diffusion bonded.

Figure 4.- Compression-specimen configurations.

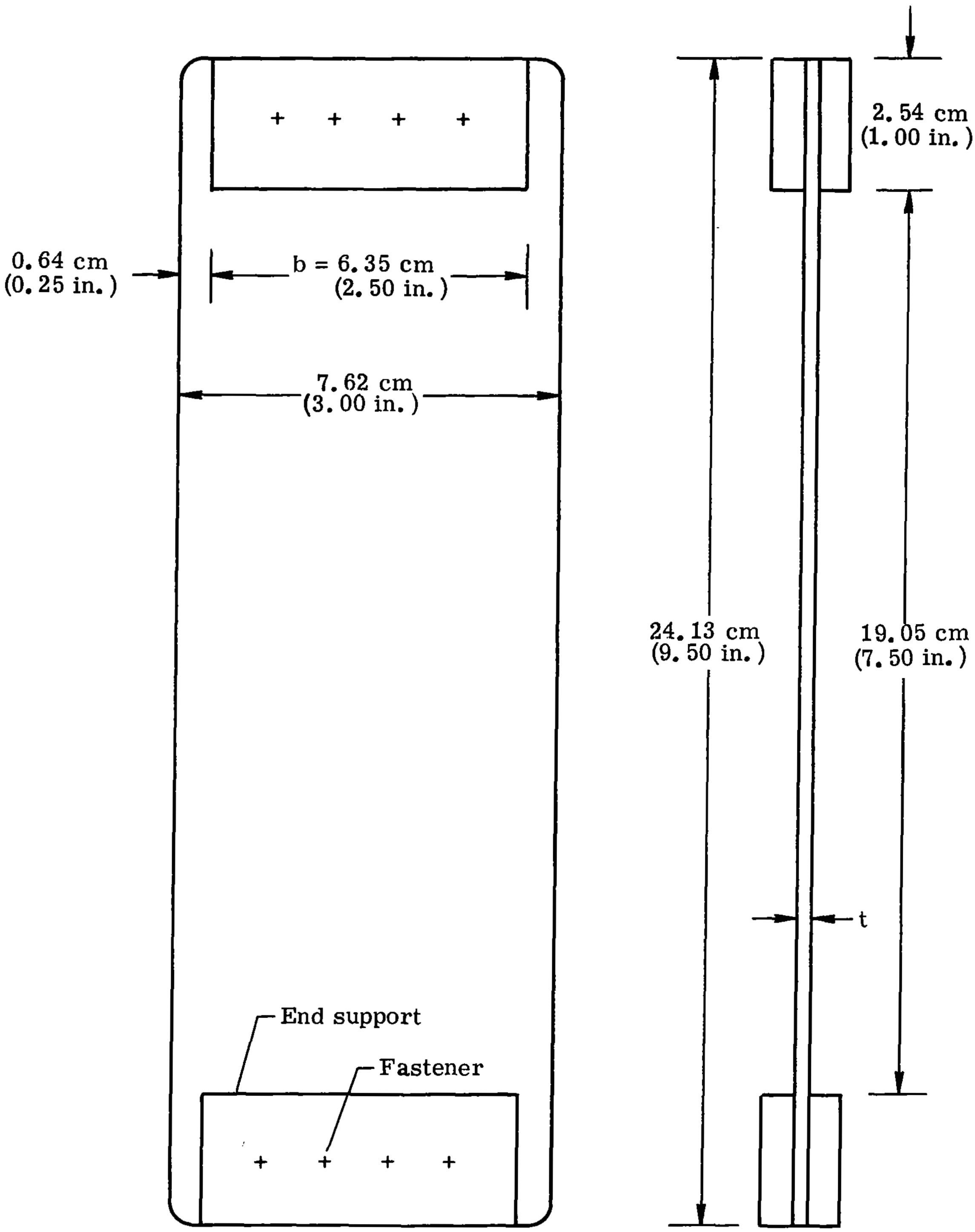


Figure 5.- Plate-buckling-specimen configuration.

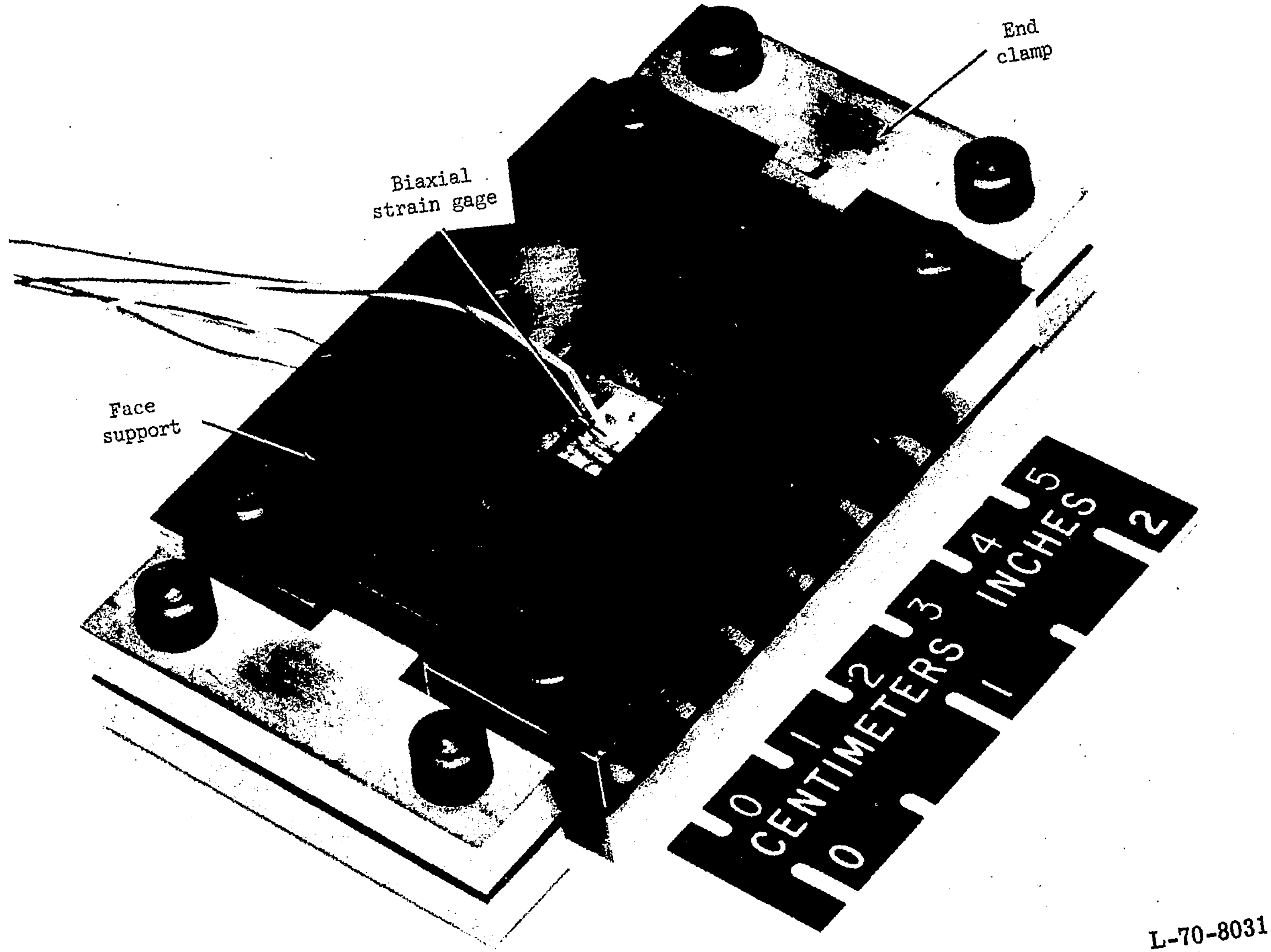


Figure 6.- Compression test fixture.

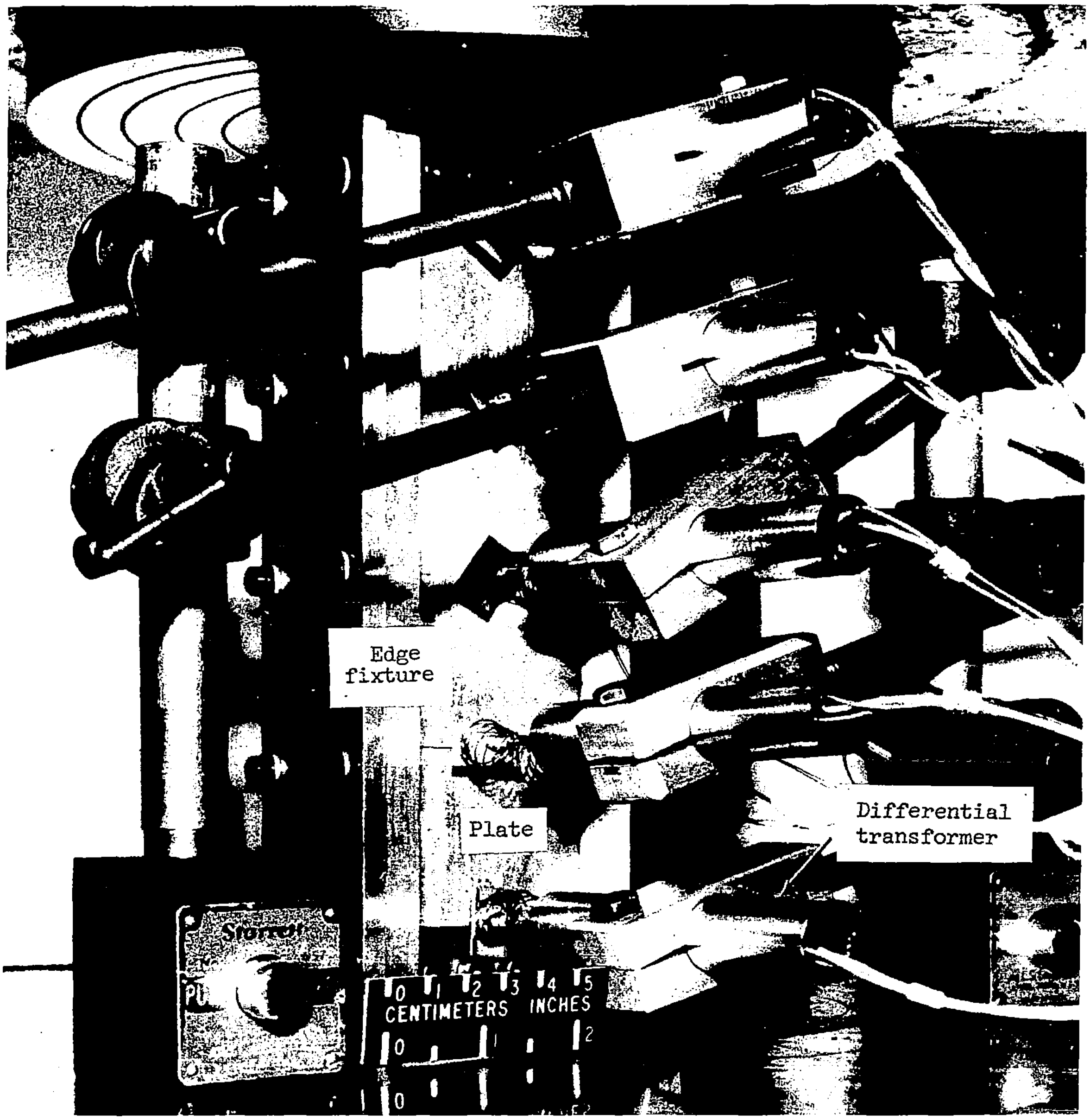


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Figure 7.- Buckling test apparatus.

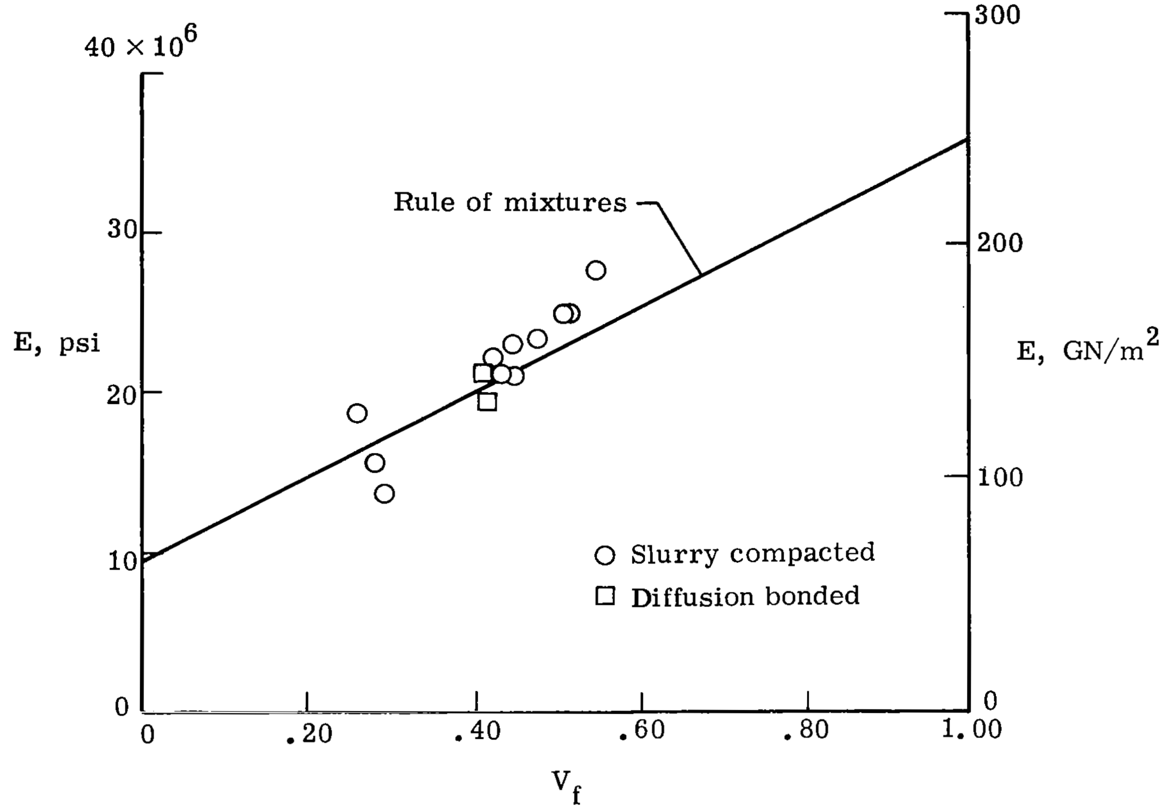


Figure 8.- Effect of filament volume fraction on experimental and rule-of-mixtures values for the tensile modulus of beryllium-aluminum composites.

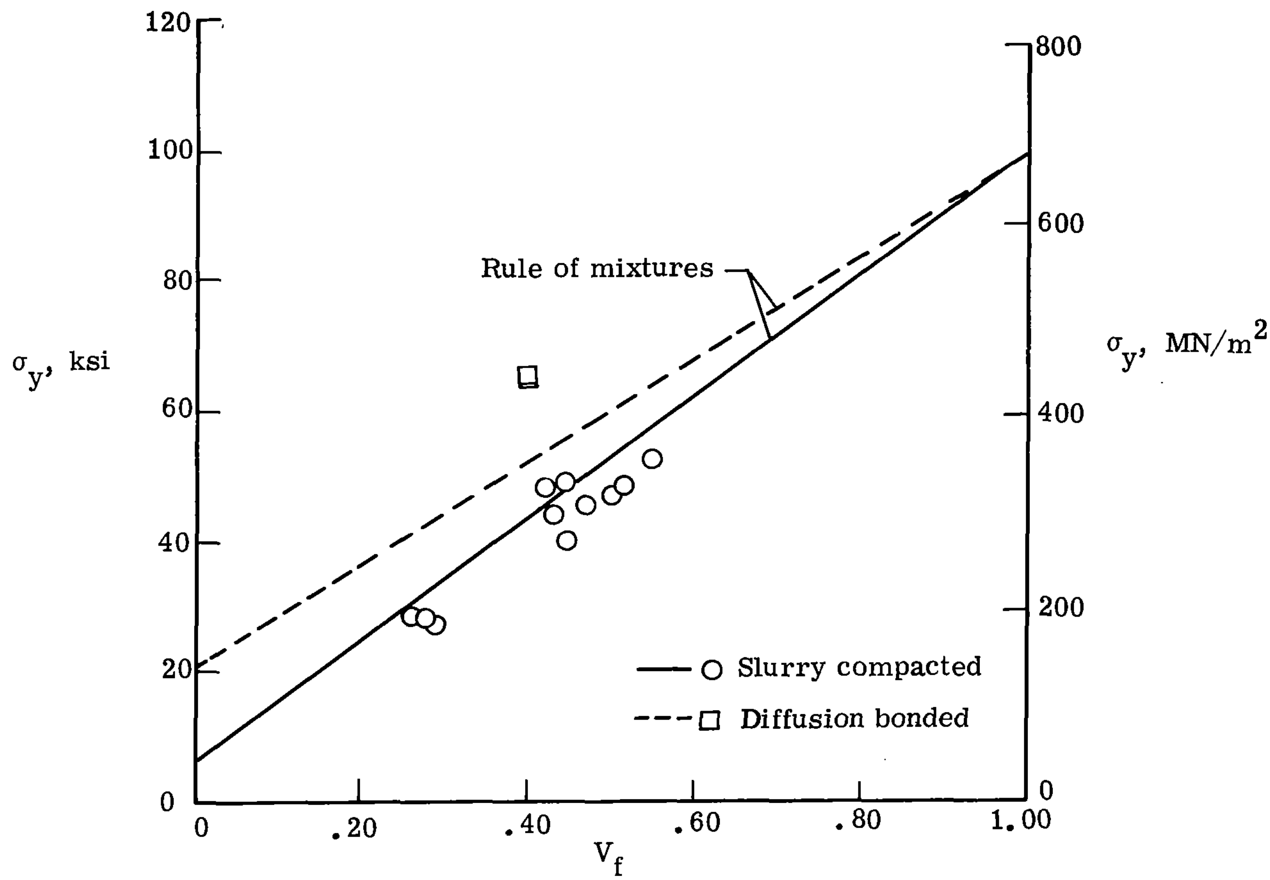


Figure 9.- Effect of filament volume fraction on experimental and rule-of-mixtures values for the tensile yield strength of beryllium-aluminum composites.

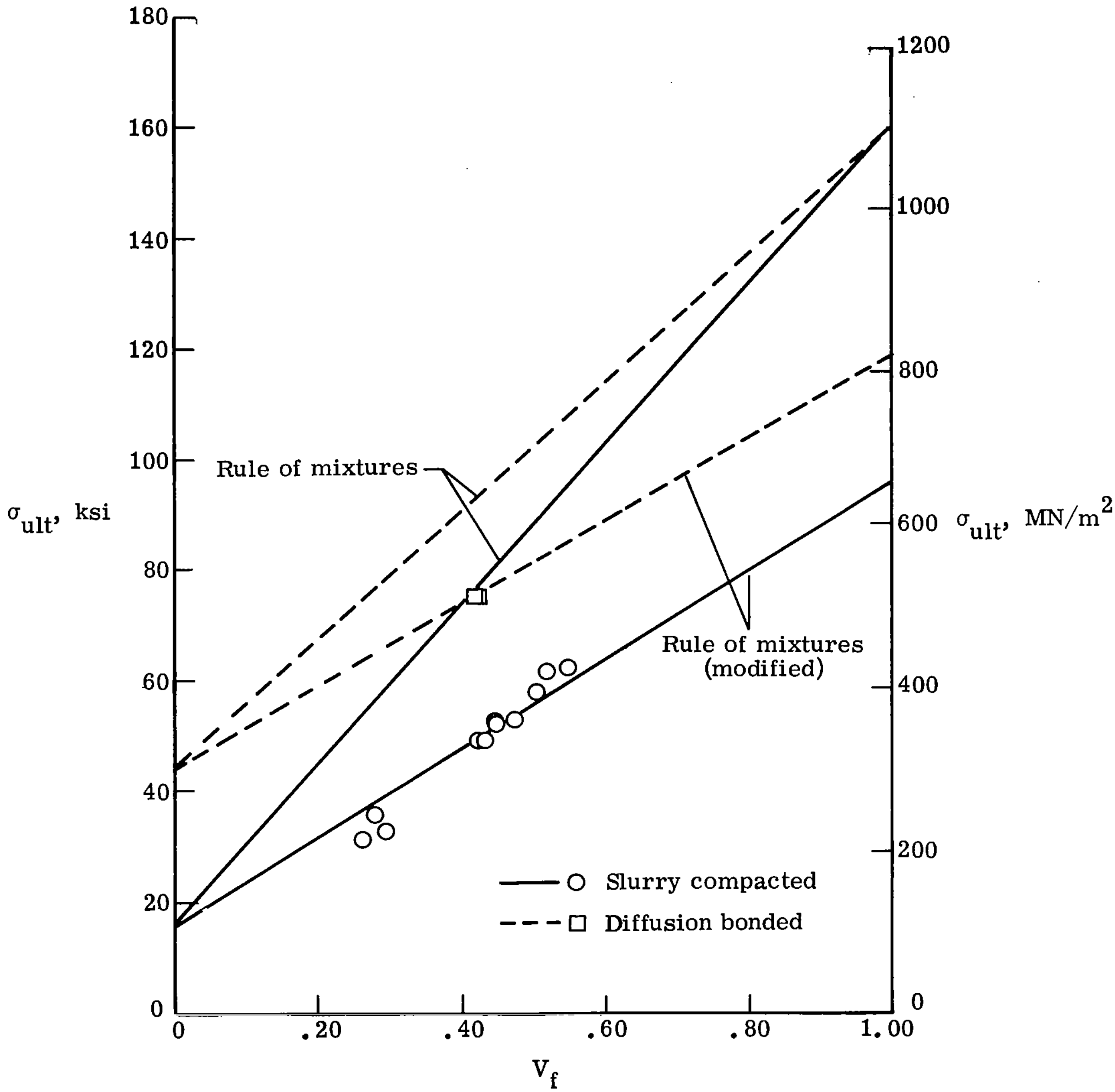


Figure 10.- Effect of filament volume fraction on experimental and rule-of-mixtures values for the ultimate tensile strength of beryllium-aluminum composites.

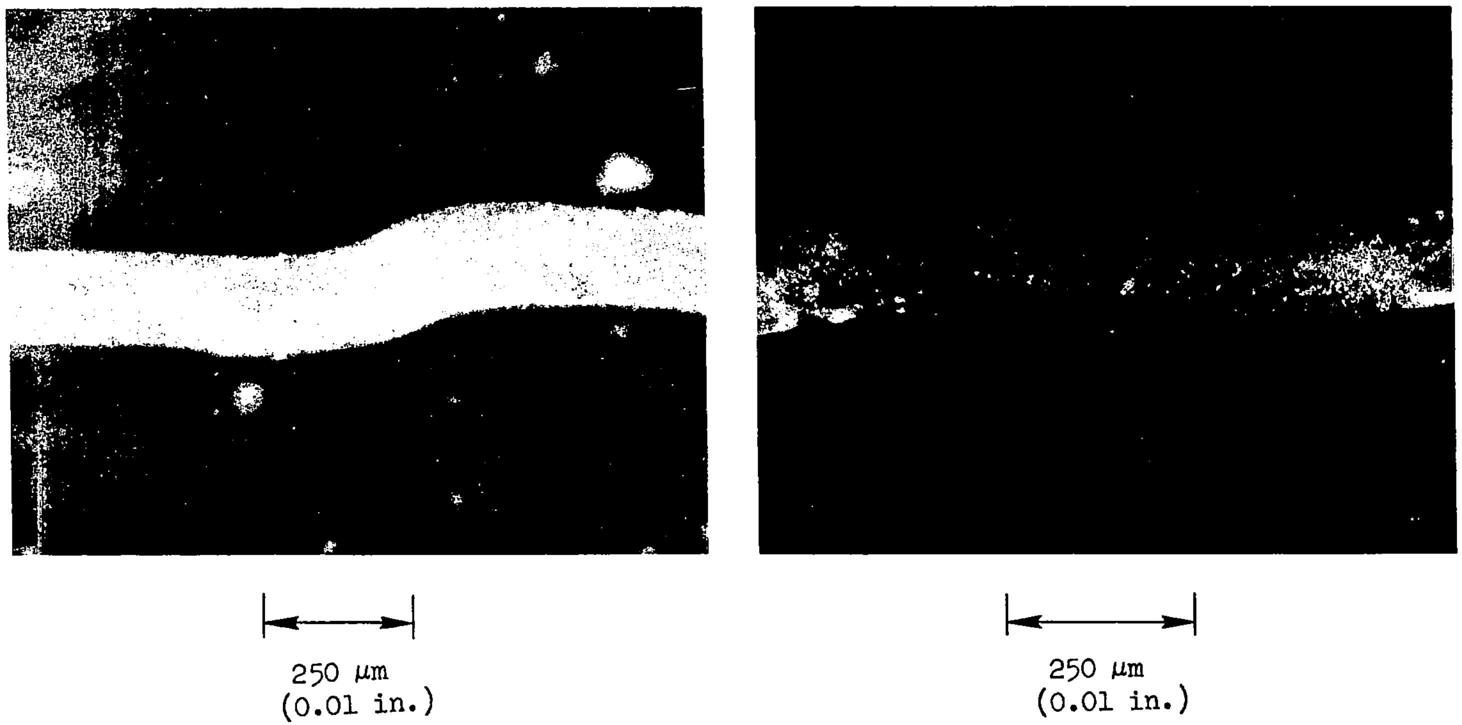


Figure 11.- Photomicrographs of beryllium filament extracted from slurry compacted composite.

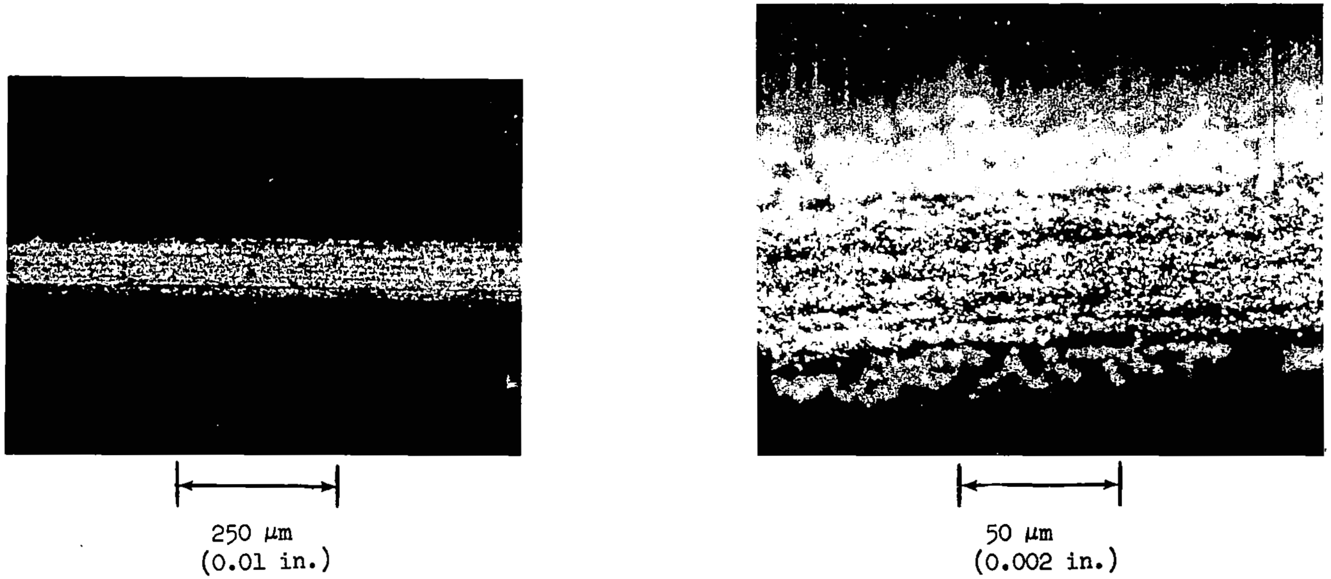


Figure 12.- Photomicrographs of beryllium filament extracted from diffusion-bonded composite.

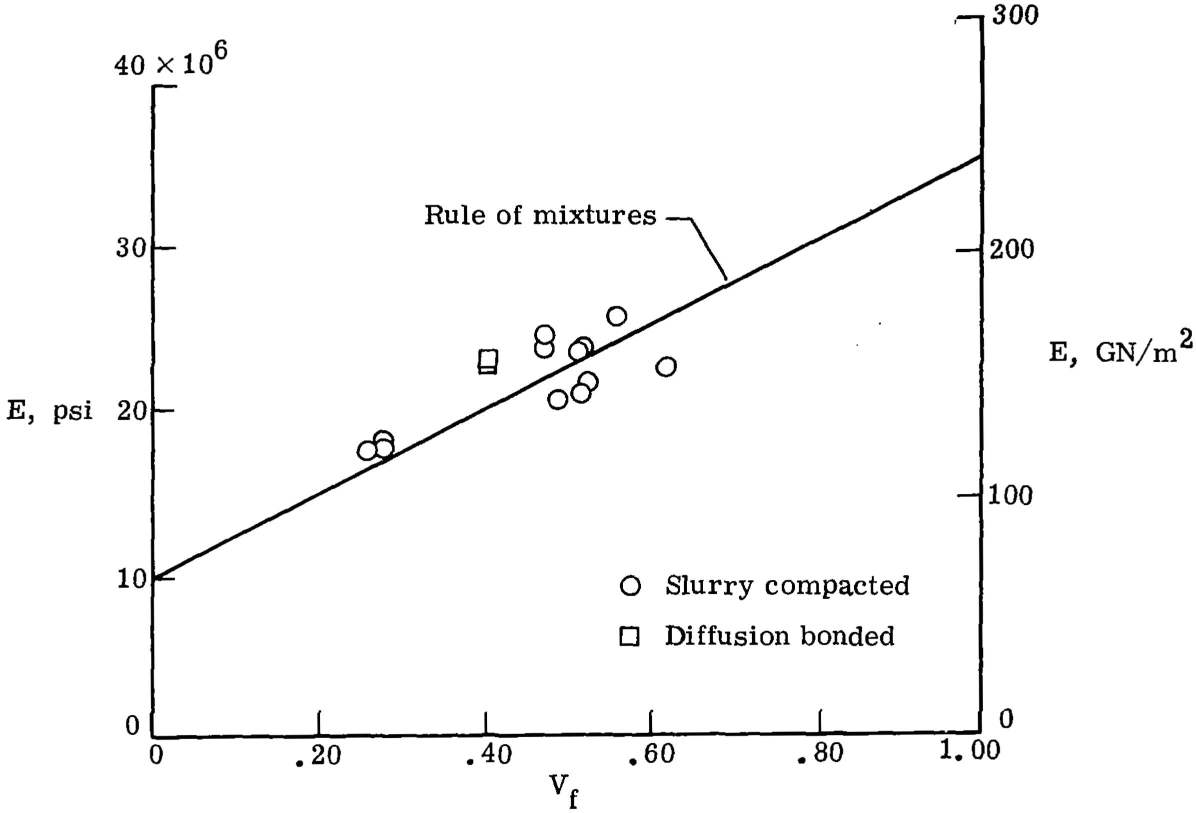


Figure 13.- Effect of filament volume fraction on experimental and rule-of-mixtures values for the compressive modulus of beryllium-aluminum composites.

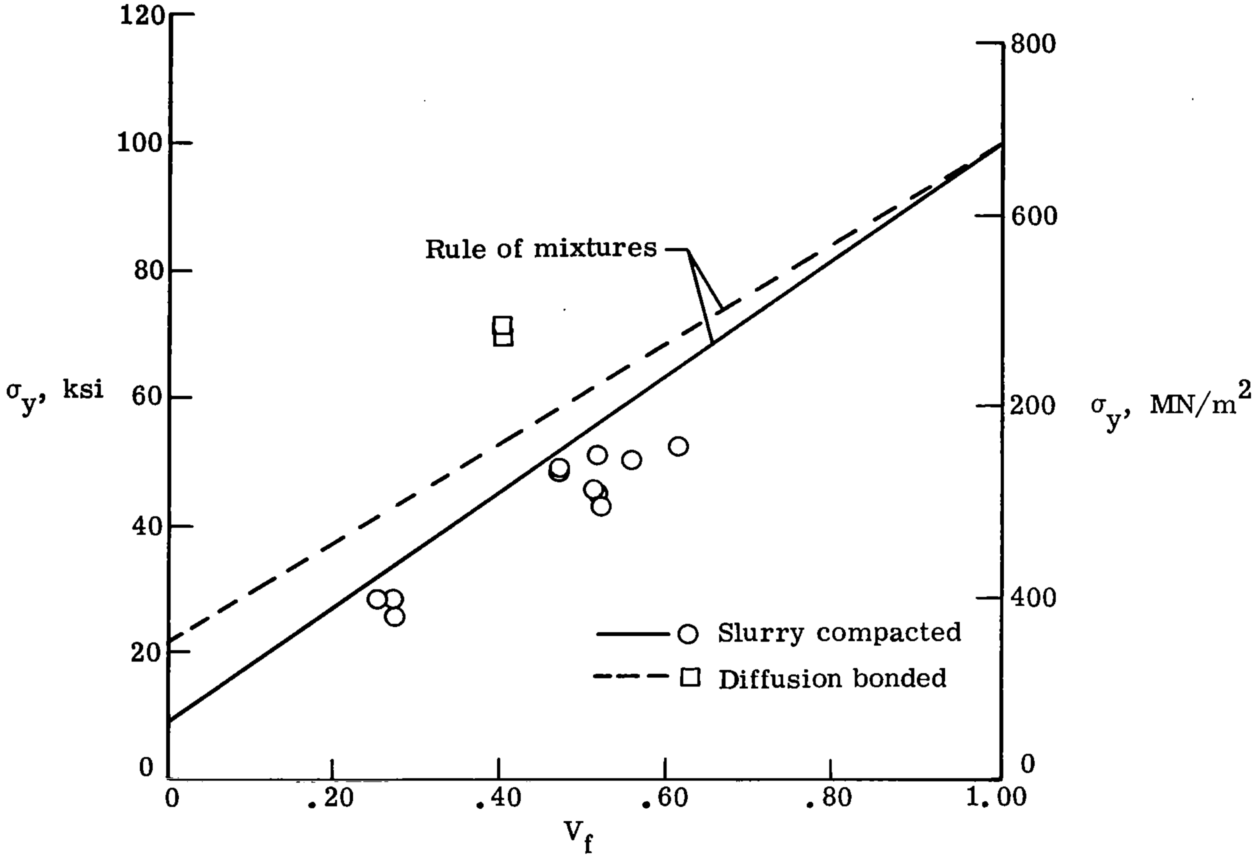
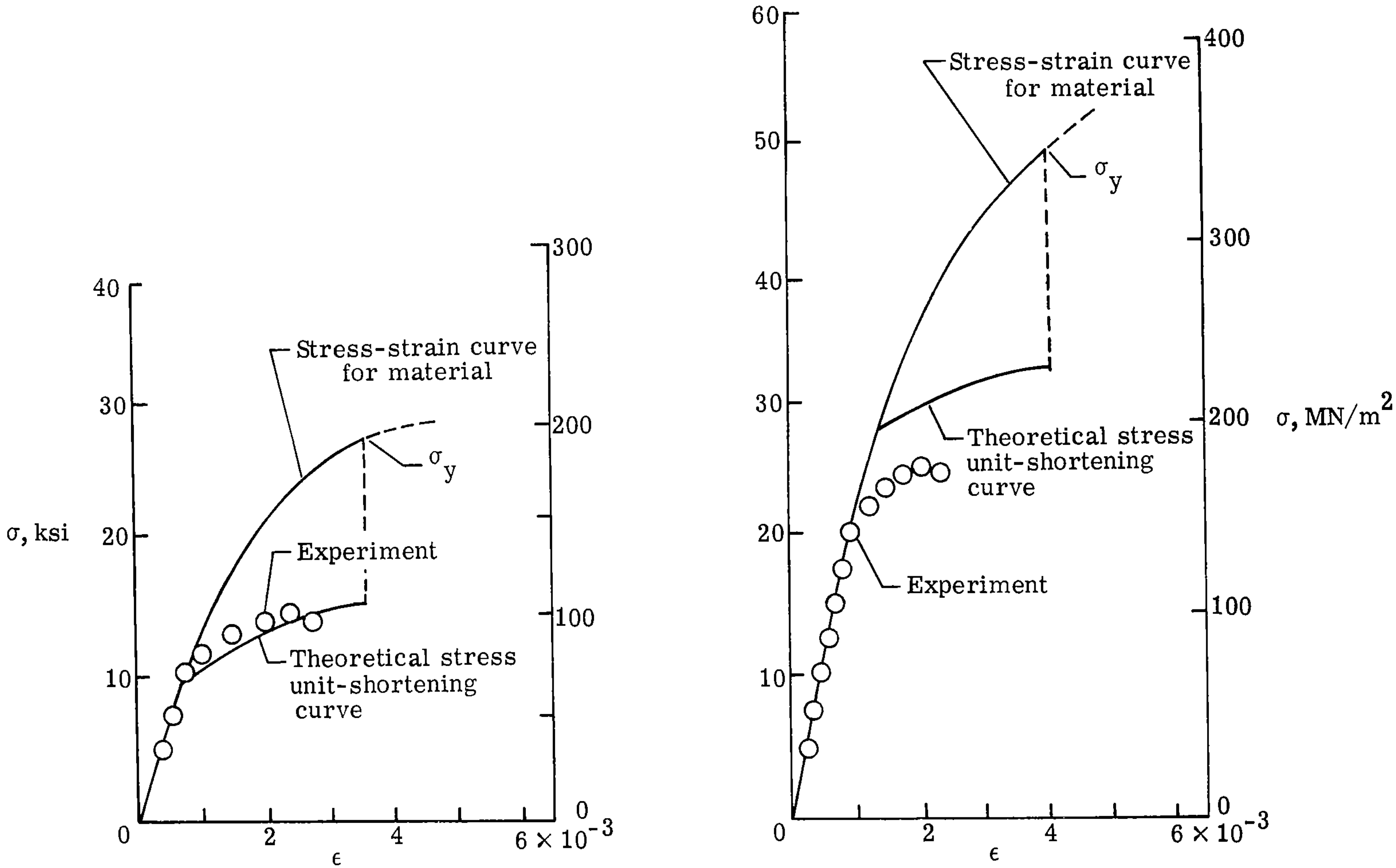
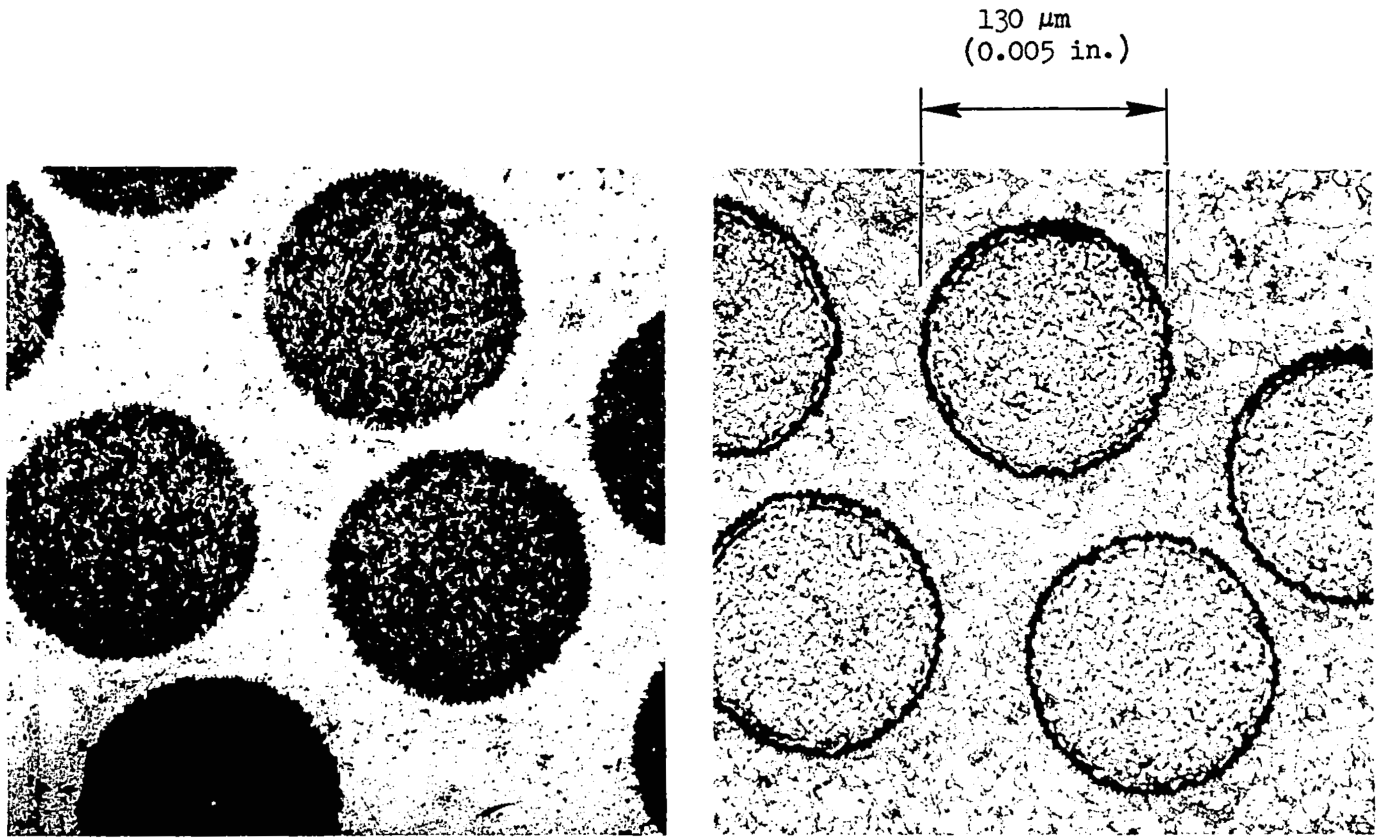


Figure 14.- Effect of filament volume fraction on experimental and rule-of-mixtures values for the compressive yield strength of beryllium-aluminum composites.



(a) Plate 1, $V_f = 0.3$. (b) Plate 4, $V_f = 0.5$.

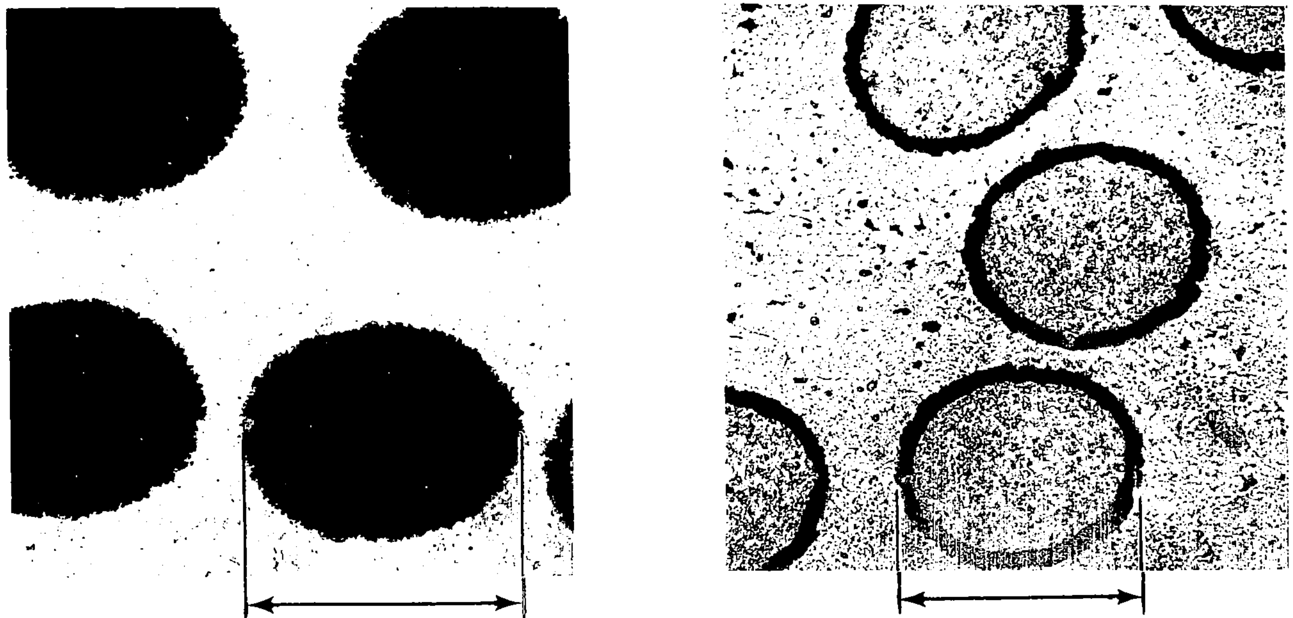
Figure 15.- Comparison of experimental and theoretical stress—unit-shortening curves for slurry compacted beryllium-aluminum composite plates.



Unetched

Etched

Figure 16.- Photomicrographs of an unetched and etched cross section of beryllium-aluminum composite fabricated by the slurry compaction process.



Unetched Etched

Figure 17.- Photomicrographs of an unetched and etched cross section of beryllium-aluminum composite fabricated by the diffusion-bonding process.

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